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The Effect of Initial and Gun Mount Conditions on the Accuracy of Kinetic Energy (KE) Projectiles

Stephen Wilkerson

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The U.S. Army Research Laboratory (ARL) has invested considerable resources in the development of numerical techniques for the prediction of kinetic energy (KE) projectile accuracy. In particular, a validated three-dimensional transient finite element (FE) model of the M256 120-mm M1A1 main weapon system's performance has been created from the trunnions up. This model considers for the first time the gun tube, breech, piston, cradle and mount assembly, along with their associated boundary conditions. This enhanced numerical approach provides new insight into occasion-to-occasion and round-to-round variability in the M256 gun system. Numerical and experimental analysis techniques have been coupled to validate model attributes.

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PREFACE

The U.S. Army Research Laboratory (ARL) has invested considerable resources in the development of numerical techniques for the prediction of kinetic energy (KE) projectile accuracy. In particular, a validated three-dimensional transient finite element (FE) model of the M256 120-mm M1A1 main weapon system has been created from the trunnions up. This model considers for the first time the gun tube, breech, piston, cradle and mount assembly, along with the associated boundary conditions. This enhanced numerical approach provides new insight into occasion-to-occasion and round-to-round variability in the M256 gun system. Numerical and experimental analysis techniques have been coupled to validate model attributes including:

- gun tube/breech pressurization,
- more accurate representation of both the gun tube profile and tube flexibility,
- a complete recoil assembly with clearances and sliding interfaces between associated parts,
- trunnion supports and the elevation mechanism.

This report presents results substantiating these claims and demonstrating the robustness of the numerical approach.

Using the enhanced M256 gun system numerical model, a detailed examination of normal propulsion variations and projectile initial malalignment effects on projectile performance has been performed. Additionally, the numerical model was used to enhance experimental findings by isolating discrete components of variability within the scope of normal gun system attributes. For example, studies of pressure variations on projectile impact locations have been coupled with possible occasion-to-occasion and round-to-round permutations that occur within the recoil alignment and projectile initial seating, respectively.

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1. BACKGROUND

Early numerical analytical studies concentrated on determining the structural integrity of improved kinetic energy (KE) projectiles. These improvements have focused, to a large extent, on reducing the sabot weight while increasing the subprojectile length and mass. As the mass of the sabot has been gradually reduced, the complexity of the design has increased. In turn, as the complexity of the sabot/subprojectile system has evolved, so has the sophistication of the numerical analysis techniques employed to analyze them. Examples of some of these techniques are given by Burns (1981).

This report presents analytical techniques that can be used to develop the in-bore structural design of saboted KE projectiles with long, high-density rods. A number of important design issues regarding saboted projectiles are also presented. For example, a methodology for the design of the sabot/rod interface is presented. Additional information on the effective design of sabot ramps and the use of two-dimensional (2-D) finite element (FE) methods for the verification of projectile structural strength is also provided. The results of these numerical and analytical design techniques were subsequently expanded for the development of very efficient projectile designs for both 105-mm and 120-mm tank guns. The report also offers a fair compendium of work performed prior to 1981 on sabot/rod systems.

Using similar numerical techniques, Drysdale, Kirkendall, and Kokinakis (1980) showed insight into how numerical modeling methods might be used to increase the performance of KE projectile designs. In this study, the requirements for a modern long rod penetrator sabot were described in terms of analysis techniques that could be employed to find the lightest possible sabot or an optimal sabot/rod configuration. Another such paper on the structural design of projectiles defines some of the problems encountered when the in-bore behavior of a projectile is considered (Drysdale and Burns 1988). These reports review many of the analytical and numerical techniques that are currently being used to develop modern projectiles.

Nonetheless, these reports point out that the techniques used thus far do not take into consideration the projectile transverse loading during in-bore travel. Such loadings, as introduced by an unbalanced breech, barrel drop due to gravity, tube heating, or a bent gun tube (gun tubes are never perfectly straight) are not considered in the initial design of the projectile. In the past, a series of experimental tests has been used for the final optimization of the KE projectile. Typically, the projectile would be designed based on known numerical and analytical design techniques. The design would then be manufactured and tested in groups of 5 or 10. Based on the results of these tests, slight modifications would be made, and the

cycle of testing and modifying would continue until an acceptable design was derived (Burns and Wilkerson 1990). Tested parameters are often evaluated from radiographs, high-speed and smear photography, velocity and target impact data, proximity probes, and yaw cards. Data were collected using these test results, which also helped to determine the structural integrity of the projectile and the sabot discard characteristics.

With the availability of high-speed computers, three-dimensional (3-D) FE techniques that can take traverse loadings into account have been applied to the study of in-bore projectile behavior (Rabern 1988, 1989; Rabern, Parker, and McAfee 1990). It is now believed that these new techniques may be capable of improving the initial and modified sabot designs of future projectiles. This ability would add significantly to the existing collection of analytical and numerical techniques that are available to aid in KE projectile design. Three-dimensional FE techniques might also reduce the number of iterations in the current, costly cycle of testing and design modification.

Rabern's early work (1988, 1989) introduced, for the first time, a methodology to characterize the performance of a projectile that was subjected to lateral and axial loading. The methodology was developed using a state-of-the-art 3-D FE approach. It was subsequently evaluated by direct comparison with experimental results. The results indicated that the phenomena observed experimentally could be accurately simulated using known numerical techniques. The experimental portion of the study involved full-scale testing of two separate sabot/rod designs in a 120-mm launch tube that was slightly bent. A 2.3-MeV x-ray unit was employed to determine the lateral displacements occurring in the sabot and rod as they traveled down the launch tube and exited at a very high speed. Due to the relatively quick ballistic cycle, on the order of 7 ms, the projectiles were subjected to significant lateral loads from the bent gun tube. After the projectile exited the launch tube, the sabot separation and rod straightness were recorded by four 150-keV x-ray units. These test results were then used to bench mark the numerical analysis.

The numerical analysis involved a 3-D model of the sabot, rod, and gun tube using the DYNA3D FE program (Hallquist and Whirley 1989, Brown and Hallquist 1984). The comparison of displacement profiles of those recorded by radiographs in the experiment and those calculated by the numerical simulations showed that this technique could yield good results. Based on that observation, it was not unreasonable to conclude that the numerical predictions for stress and strain would track equally well. The study also performed a series of calculations to determine the sensitivity of the mesh refinement.

These calculations revealed that the method was converging when more than 5,000 elements were used. At this point in the mesh refinement, the calculations were within 1% of one another. The actual FE model of the sabot and rod was made from a half-symmetric or 180° slice. This half-symmetric model was used for simplicity and enabled the isolation of the vertical displacements induced into the projectile from the bent gun tube. Most importantly though, the study proved that parameters like the strength profiles of bent gun tubes can be accurately simulated in a 3-D analysis. Moreover, the work provided the opportunity for the various aspects leading to projectile lateral loads (e.g., unbalanced breech, bent tubes, initial conditions, etc.) to be studied individually or collectively using modern numerical analysis.

In a subsequent study (Rabern, Parker, and McAfee 1990), it was shown that small differences in the projectile initial seating could lead to significant changes in the projectile lateral velocity and rotational rates at muzzle exit. This work concentrated on a comparison between various initial conditions for 105-mm XM900E1 projectiles. These included pitched-up, pitched-down, and aligned conditions as well. Additionally, a nonrotating condition was analyzed to examine the effects of rifle-twist on the projectile motion. The numerical simulation used a full 360° model of the projectile and gun tube to examine both horizontal and vertical displacements, velocities, and rotational rates of the sabot/rod at muzzle exit. This model does not discard the sabot from the rod at muzzle exit as would occur in reality.

In a connected effort, Hopkins (1990) related the importance of gun tube pressurization while, for the first time, demonstrating methodologies to include pressurization effects in the FE analysis of a gun system launching of a bullet. Afterwards, Rabern and Lewis (1992) incorporated a traveling pressure front into a full 3-D model and examined the dynamic response of the projectile and gun together. In addition, Hopkins and Wilkerson (1993) examined the accuracy of various methods to incorporate traveling pressure fronts in 3-D FE models of gun systems.

Although some gun and projectile interaction problems are beginning to be addressed with 3-D FE techniques, questions pertaining to the effects of the gun system recoil mechanism have just recently begun to be studied. Using a series of small scale experiments (Wilkerson, Fulton, and Thiravong 1993; Wilkerson, Burman, and Li 1993) and some numerical studies (Wilkerson 1993; Wilkerson and Hopkins 1994), simulations of the recoiling motion of the M1A1 main weapon system have been conducted. In these recent models, an M256 120-mm gun system was modeled from the gun tube to the trunnion, which mount the gun and recoil system to the M1A1 turret.

Figure 1 shows a cutaway view of the M256 120-mm gun system. As shown in the figure, the system consists of a complicated series of components that have varying clearances which can slide relative to one another during the recoil and counter-recoil strokes. To model these parts using FE techniques required careful scrutiny of the drawings and actual hardware. Observing the assembly and disassembly of parts during routine maintenance provided additional insight about clearances between associated parts. The primary parts (labeled in Figure 1) were first modeled using a Computer-Aided-Design (CAD) package (Autodesk Inc. 1987). These CAD models served as the basis for the FE representation of the M256. Figure 2 shows the CAD approximations of the M256 major components. The FE model of these parts was constructed primarily from eight nodded brick elements as well as linear spring elements.

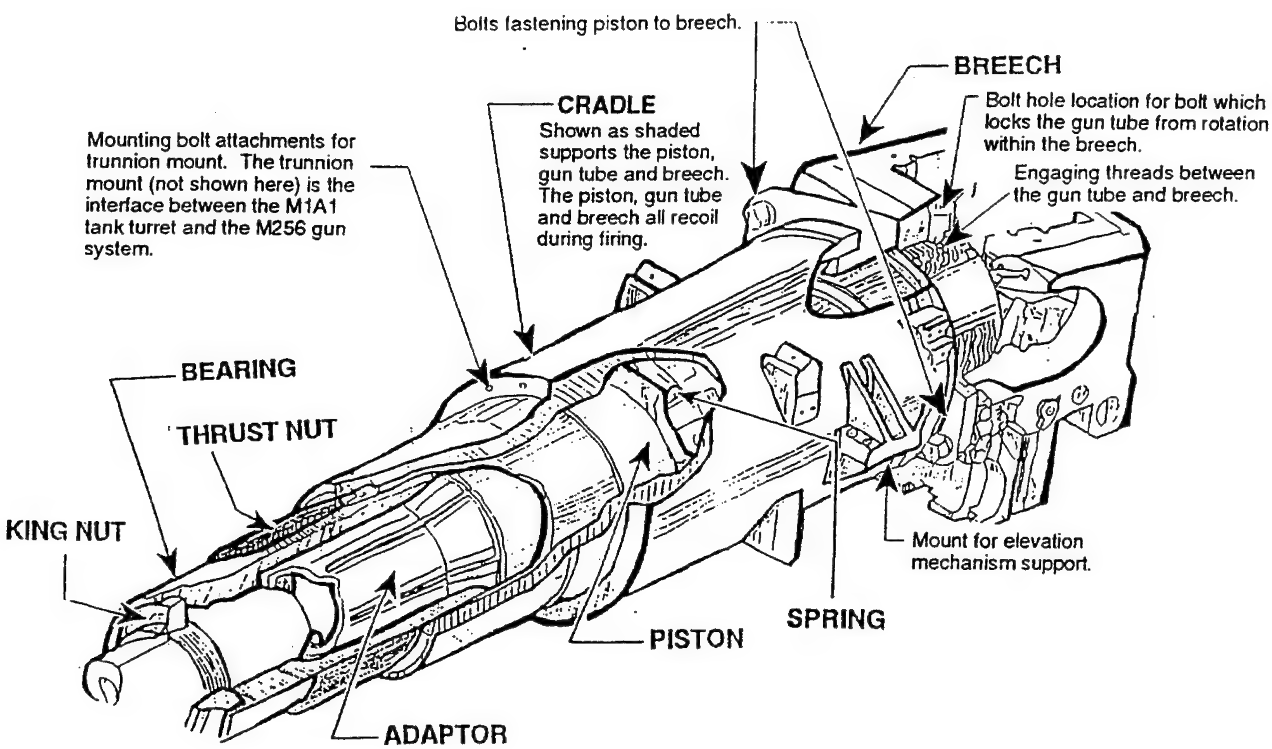

Figure 1. Cutaway view of the M256 120-mm gun recoil system.

The first two pieces modeled were the gun tube and breech. In the actual assembly, these two parts are engaged with an interrupted thread. The gun tube slides inside the breech and is then rotated 45°. The opposing threads on the breech and gun tube tightly connect the two parts. Finally, a bolt is threaded through the upper portion of the breech and into a corresponding notch in the gun tube to limit relative rotation between the two parts. While these components have some clearances between them for ease of installation, their axial movement is heavily coupled. The relative vertical and horizontal motion between the parts is also very closely coupled.

Being unable to ascertain the relative movement between the piston and gun tube along the rear contact point, it was assumed that these components respond as if they were rigidly connected. In addition, the piston bolts to the breech at two locations across its rear face, which adds rigidity to this connection. Just forward of that location on the gun tube, the piston radially supports the gun tube at two contact points. To simplify the model, these two axial locations are merged. Along the forward end of the piston, a series of parts are used to secure the gun tube to the piston. This clamping device consists of the adapter, bearing, king nut, and thrust nut (Figures 2 and 3).

These parts form a fairly rigid clamp between the piston and gun tube. In addition to the piston and gun tube attachment, the piston is supported inside the cradle. The cradle allows the gun, breech, and piston to recoil during firing. Creating a model of the cradle attachment points, particularly at the front of the piston, is non-trivial.* Therefore, a series of static load experiments were conducted to determine how to best model the supporting interfaces between the piston and cradle. The results of these experiments are reported in Wilkerson, Fulton, and Thiravong (1993). These experiments validated the assumption that the piston and gun needed to be modeled as two parts using rigid attachment points between them. Measurements confirmed that when transverse forces are applied to the gun tube, the gun and piston essentially move together. However, the measurements also indicated that the same out-of-plane forces produced relative motion between the piston and cradle. This series of static load experiments confirmed that the gun tube, breech, and piston interfaces could be modeled, at least initially, as rigid contact points. Finally, the FE model of the piston which includes the adapter, bearing, king nut, and thrust nut was modeled as a single component. In the model, these parts connect the gun tube and piston at the same location as the actual contact points on the M256. The assumption of a rigid contact undoubtedly makes the overall system stiffer than the actual gun. The effect of this approximation

* These parts are not, in most cases, rigidly attached to one another.

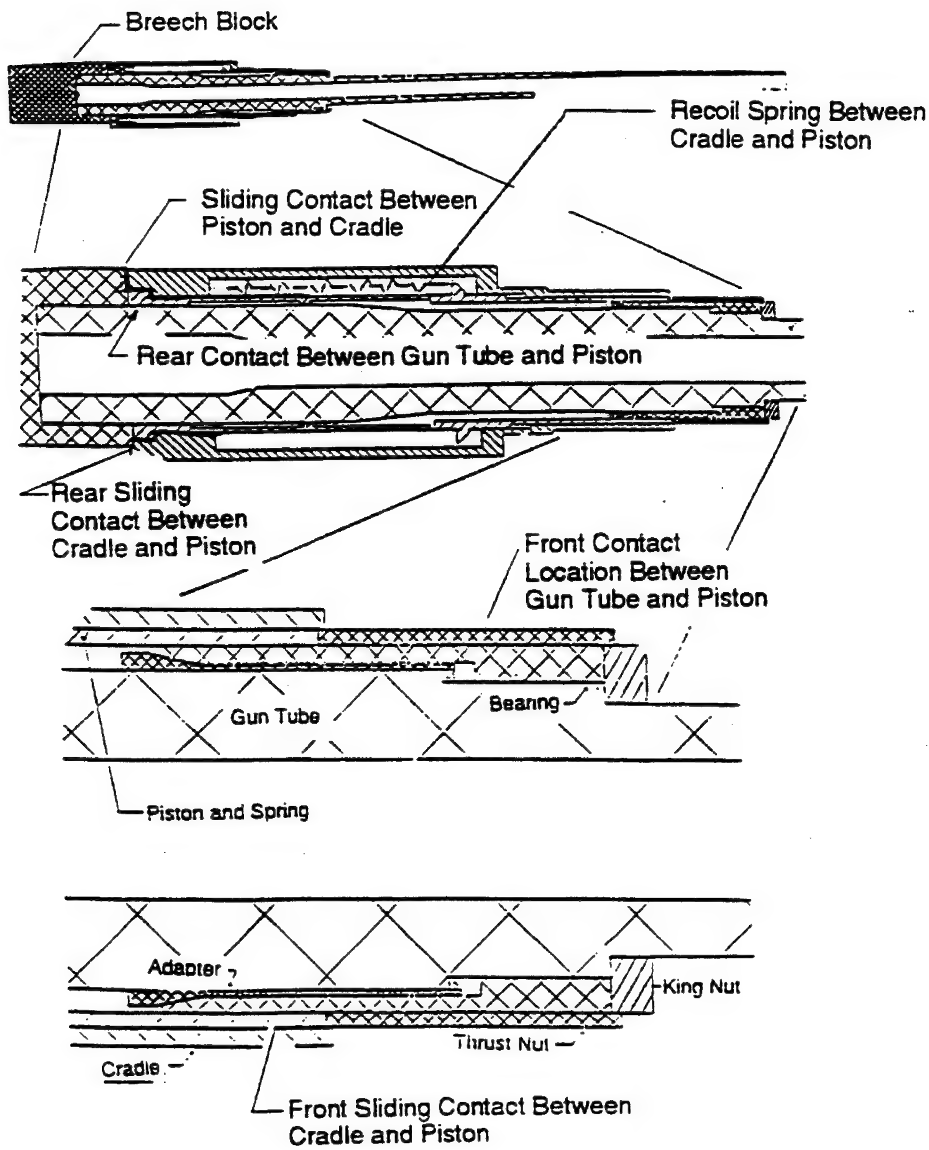

Figure 2. CAD drawing of M256 main components.

will be further investigated in future models. Nonetheless, for the purpose of this study, the effects of this assumption are negligible. Figure 4 shows the FE model developed for these three primary parts.

The gun tube, breech, and piston are supported in the tank turret by the cradle. The cradle connects to the tank turret through the mantlet that has a pair of trunnions supported by the turret and the elevating mechanism. The trunnions allow free rotation of the cradle while the elevating mechanism controls that rotation. The cradle sliding support for the piston also allows the gun tube, breech, and piston to recoil

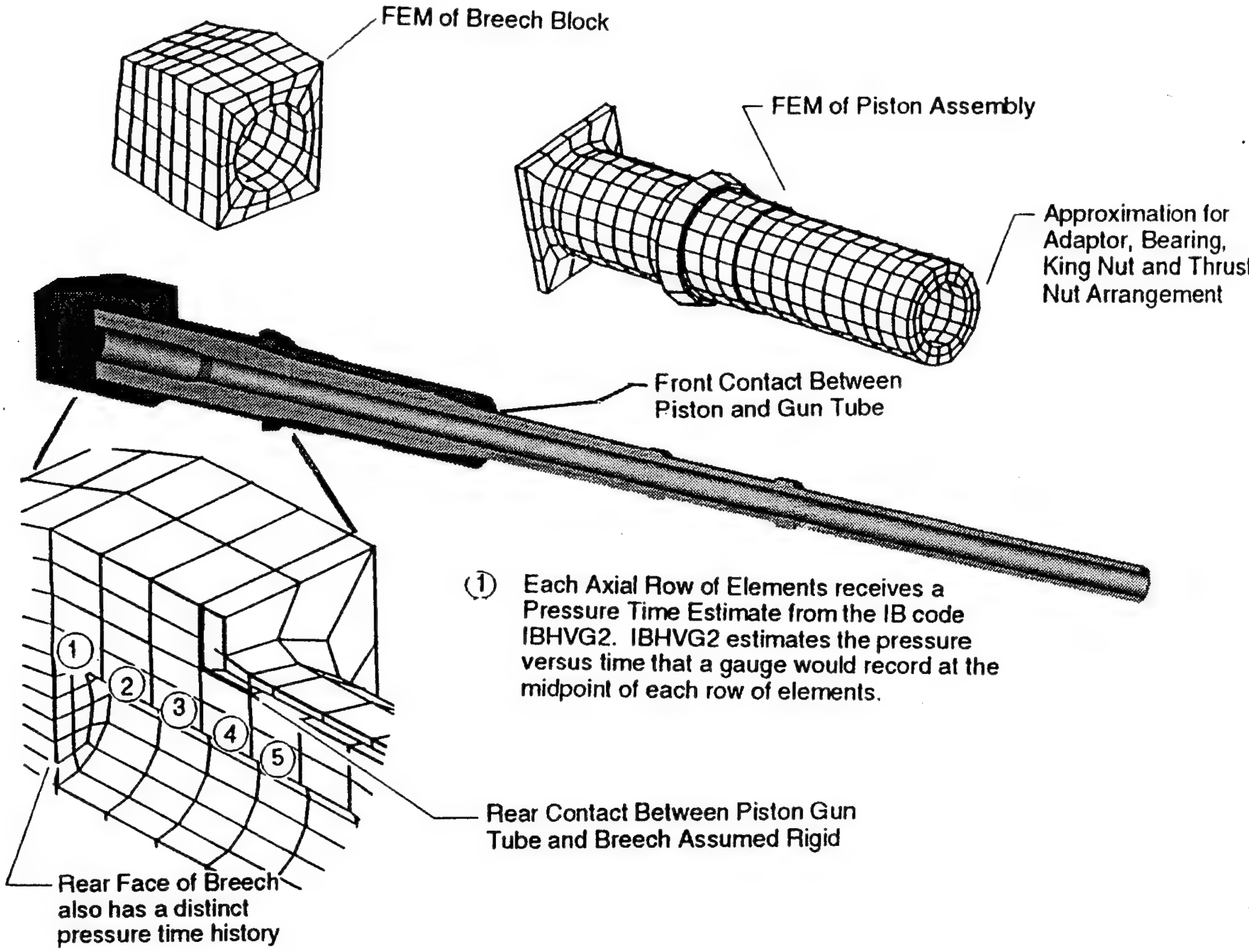

Figure 3. FE representation of gun tube breech and piston assembly.

during firing. Therefore, it was necessary to model these interfaces using the sliding contact capabilities in DYNA3D (Hallquist and Whirley 1989). The clearances between these sliding contacts, which were observed to influence movement of the system during the static load experiments, are of paramount importance in estimating the changes in response between the balanced and unbalanced systems. The incorporation of this important attribute is discussed in detail in Wilkerson and Hopkins (1994).

The recoil consists of a large spring and damper that absorb the gun recoil energy. The gun tube, breech, and piston recoil approximately 11 in during gun firing. A number of simpler beam element models have been used to determine the best method to model the recoil behavior. During the recoil stroke, considerable energy is absorbed from the system through damping. Therefore, to model the

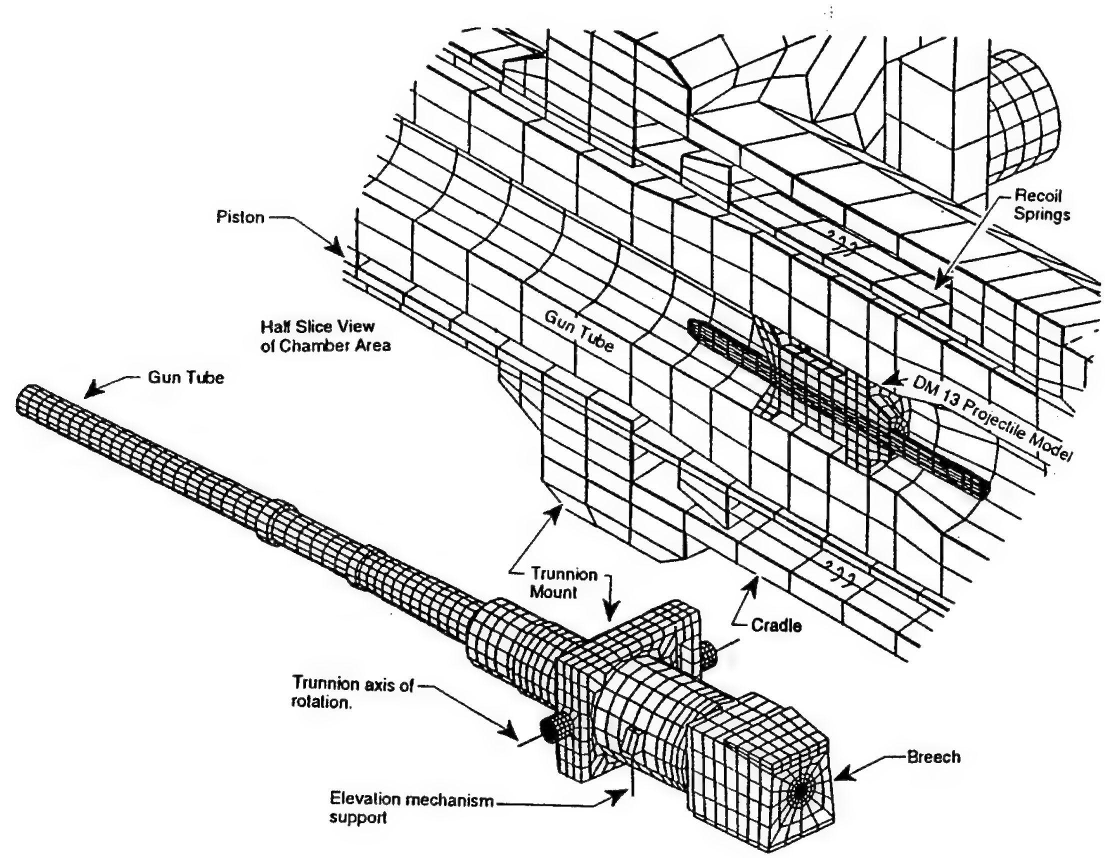

Figure 4. DYNA3D FE model with cutaway view of chamber area.

entire stroke, it is necessary to include a preloaded spring, as in the actual system, and a damper unit. However, since the gun recoils only about 1.5 in before the bullet exits the gun, and this study is primarily interested in the gun system motion while the bullet is still in-bore, the entire recoil stroke was not modeled in the simulation. Consequently, this model utilized only a simple undamped spring to simulate the recoil system behavior while the bullet remained in-bore. The validity of these assumptions was ascertained by comparing axial recoil motion predicted by the model with experimental data from an actual firing cycle. This comparison confirms that neglecting damping during early time motion (approximately the first 7 ms) has little effect on model accuracy.

The M256 cradle and recoil assembly is bolted to a metal mount with trunnions. The gun system is free to rotate about the trunnions. Only the elevation mechanism restricts movement in this plane. The elevation mechanism is a hydraulic actuator used to aim the weapon in the vertical plane. The model includes approximations for these important boundary constraints. Figure 4 shows the trunnion and elevating mechanism as represented in the FE model. As can be seen in the figure, the model is supported

by trunnions whose axis of rotation in the x-y plane is at the same approximate location as the actual system. The cradle rotation is controlled via a spring element located in a position that closely mimics the actual system.

While it is recognized that the dynamics of the elevation mechanism are nonlinear, they were modeled using linear approximations based on results from the static load experiments (Wilkerson, Fulton, and Thiravong 1993). Furthermore, this assumption seems reasonable since the system displacements are on the order of one-tenths of a millimeter, before the projectile exits the muzzle, while the nonlinear attributes of the elevating mechanism are evident only for much larger displacements. Therefore, the assumption of linearity for the cases represented here seems reasonable. The components of the final model have the same approximate thickness, weight, moments of inertia, and CG as the actual parts in the M256 (Wilkerson, Berman, and Li 1993). The DYNA3D FE program was used to run the simulation, while the PATRAN and PATDYN translators were used to post-process the results (Hallquist and Whirley 1989; PDA Engineering 1987a, 1987b).

The centerline profile of gun tube No. 5064 was used in the analysis presented here in accordance with the techniques discussed by Wilkerson (1993). Basically, the techniques used to incorporate a particular gun tube centerline profile correlate the technologies used to measure gun tube centerline with FE calculation of gravity droop. In particular, gun tubes are measured while being supported in a fashion that is similar to the actual gun tube support in the gun mount. However, when the gun is fired, there are devices attached at various locations along the gun tube (such as the bore evacuator, thermal shrouds, and muzzle reference system) that change the tube centerline profile from that originally measured. The methods discussed in Wilkerson (1993) make allowances for additional mass to be included in the model of the gun tube by recalculating the change to the centerline profile accordingly. For this study, tube No. 5064 was chosen because it was also one of the tubes used during the balanced breech experiments (Held and Erline 1991).

The projectile model was a simplified version of the DM13 projectile (Figure 5) because it was one of the KE projectiles used during the balanced breech experiments. The procedures used in the projectile model were similar to the procedures used by Kaste and Wilkerson (1992) for the XM900E1 projectile. The one notable difference was how the treatment of interferences between the sabot petals was handled. In this study, the motion of the gun system was of primary importance; with the projectile motion and its

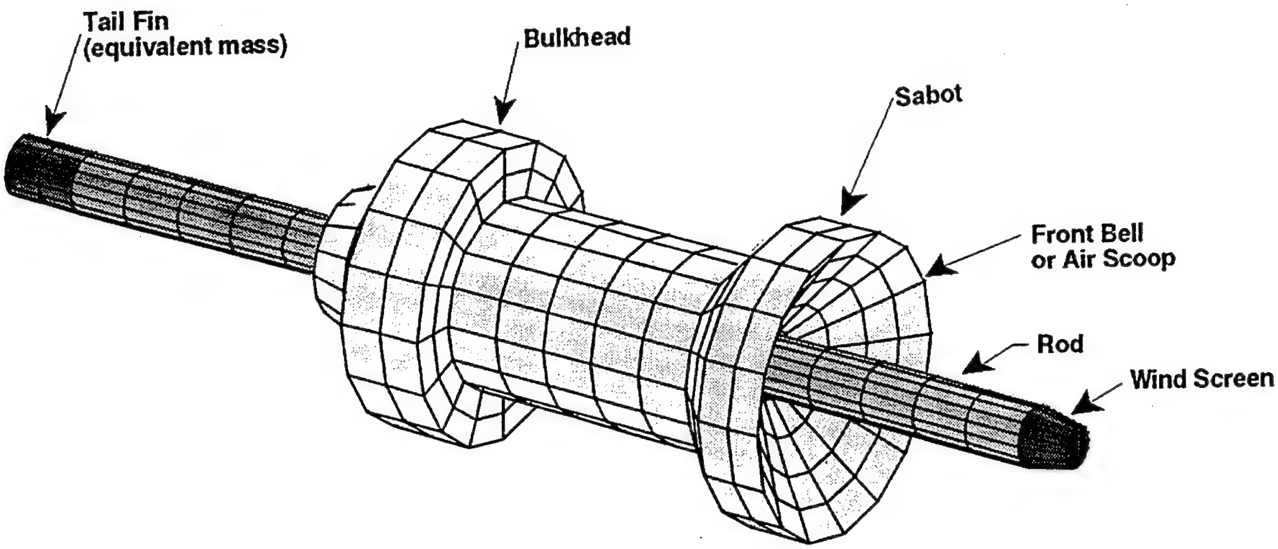

Figure 5. Model of the DM13 KE projectile.

interactions with the gun system being of secondary importance. Hence, to reduce run times, the interfaces between the sabot petals are not modeled. In other words, the sabot itself is modeled as a one-piece component. However, the rod, wind screen, tail fins, and interfaces between the sabot and rod were also included in this model as was done for the XM900E1 projectile by Kaste and Wilkerson (1992). In particular, the wind screen and tail fins are approximated using a lumped mass approach as described in Kaste and Wilkerson (1992).

To simulate the proper ballistic environment inside the 120-mm gun during a firing event, pressure-time estimates based on an actual shot were made using the IBHVG2 interior ballistic (IB) code (Anderson and Fickie 1984). The calculations provided pressure-time histories as a function of projectile travel along the axial length of the gun tube. In the model, the inside face of each axial row of elements comprising the gun tube received a unique pressure-time curve to simulate the actual pressure across the inside wall of the gun tube. Additionally, the inside breech face, which is exposed to the chamber pressure, also had a distinct pressure loading history. Finally, an estimate of the pressure along the rear surface of the projectile was included. The rear surface of the projectile is considered to be any portion of the projectile that would be exposed to the burning propellant gasses. In all, 70 unique pressure-time load curves were used in the FE model simulations.

It has been shown that calculations made using the DYNA and NIKE (Brown and Hallquist 1984) family of codes for projectile displacement, velocity, and acceleration, using the above assumptions, very closely duplicate the predictions from an IB code (Wilkerson 1991). Results are typically within 1–2% of more accurate modeling approaches (Hopkins and Wilkerson 1993). Noting that the pressure at any axial location of the tube is primarily dependent on the projectile position, and that this attribute has been shown to be accurately predicted by the DYNA and NIKE codes, the pressurization of the gun barrel is also reasonably accurate. As a check of this assumption, calculations were made on a generic gun tube to estimate the influence of axial grid spacing. Calculations were made using the unique pressure-time curve at each axial location and compared to a coupled calculation where the FE and IB codes are linked together. In the latter calculation, DYNA results for projectile displacement, velocity, and accelerations were fed back into the IB code and the pressure at every location was calculated based on this information at each time step (Hopkins and Wilkerson 1993). Without this coupling, the IB code uses a lumped mass approach to model the projectile and its equations of motion. When the codes are coupled, the pressure along the interior gun tube wall can be calculated very accurately as the projectile moves down the tube, exposing the surface to the propellant gas pressure.

It was found that for any reasonably finite discretization, the FE model and its associated set of load curves resulted in reasonable estimates for displacements, stresses, and strains. The current process of applying individual pressure curves at various axial locations along the tube length was adapted for its simplicity in application, although future models may include the more accurate coupled approach.

2. ANALYSIS

The sophistication and flexibility of the 3-D model allow issues pertaining to occasion-to-occasion and/or round-to-round variability to be examined independent of one another or in combination. For this particular analysis, the variations in exit shot conditions are used as a gauge of the round-to-round variation. One typical parameter that can change from round to round of a given ammunition type is the pressure variations in the propellant bed (Robbins 1994). A typical example of pressure variations was accomplished by changing the pressure on the back of the projectile by ±4% the norm (Robbins 1994).* The results from these calculations are given in Table 1.

* This value was estimated as "typical" of what could occur; not necessarily the largest or what happens every time a 120-mm gun is fired with a KE projectile. In other words, this value represents a typical high value.

Table 1. Gun Tube Tilted With Clearances, Unbalanced

Pressure Percent (Maximum)	Average y Velocity (in/s)	Average z Velocity (in/s)	Pitch Rate (rad/s)	Yaw Rate (rad/s)
0.96	39.2	11.6	15.9	4.7
1.00	40.4	11.5	14.8	4.1
1.04	37.3	12.6	13.6	4.1

Table 1 is labeled as: "Gun Tube Tilted With Clearances, Unbalanced" —in reference to the recoil configuration.* This particular scenario is what is currently believed to be standard, or normal, configuration for the M256 120-mm mounted in the M1A1 tank.† Then, applying ±4% pressure variation to the back of the projectile, variations in shot exit conditions can be used to quantify the effect of normal pressure deviations. Table 1, column 1, gives the percent of the total pressure on the base of the projectile. Columns 2 and 3 give the vertical and horizontal velocities in inches per second, respectively. Columns 4 and 5 give the pitch (vertical) and yaw (horizontal) rates in radians per second. As can be seen in this table, the variance is small between the associated pressures.

Initially, when the balanced breech experiments (Wilkerson and Hopkins 1994) were analyzed, several different configurations for the recoil of the gun were examined. One such variance is presented in Table 2. Table 2 contains the same pressure variations as in Table 1 only for the case of a balanced breech. For the balanced breech block, the change in exit state conditions between the various pressures was of similar magnitude as for the unbalanced breech. However, the change between the balanced and unbalanced breech results, particularly in the vertical components of velocity and pitch rate, were substantial.

* "Unbalanced" refers to the fact that the breech block on the M256 120-mm gun system is slightly offset from the gun tube's centerline. That is, the top of the breech is cut at an angle so the gun can be aimed downward without having the breech hit the top of the turret. This design results in an asymmetric breech block.

† Within the gun recoil, there exists small clearances between parts. They are on the order of several thousands of an inch. In the current analysis, the clearances between the cradle and piston are included in the model (see Figures 1 and 2). However, in the M256 recoil, there are kick blocks that engage the breech block as it returns into battery, and forces it to sit in the cradle the same way every time. These blocks push the breech and piston toward the top of the cradle. This position, and the resulting motion caused when the gun is fired, were thought to be the cause of puzzling experimental measurements of the breech movement during the balanced breech experiments (Held and Erline 1991). Later, this theory was tested with the current model, which showed this to be the case (Wilkerson and Hopkins 1994).

Table 2. Gun Tube Tilted With Clearances, Balanced

Pressure Percent (Maximum)	Average y Velocity (in/s)	Average z Velocity (in/s)	Pitch Rate (rad/s)	Yaw Rate (rad/s)
0.96	21.4	11.8	6.6	3.7
1.00	19.6	10.8	5.8	3.0
1.04	17.1	10.7	5.2	2.9

Two other configurations that were examined numerically during the balanced breech simulations are presented in Tables 3 and 4. In these two cases, the clearances between the cradle and piston were eliminated, and the recoiling parts were no longer allowed to sit at an angle inside the cradle mechanism. Table 3 represents the unbalanced breech with no clearances between the cradle and piston and Table 4 represents the balanced case.

Table 3. Gun Tube Without Clearances, Unbalanced

Pressure Percent (Maximum)	Average y Velocity (in/s)	Average z Velocity (in/s)	Pitch Rate (rad/s)	Yaw Rate (rad/s)
0.96	20.1	4.4	7.4	1.0
1.00	21.0	6.2	7.0	1.1
1.04	19.8	7.5	6.6	1.0

Table 4. Gun Tube Without Clearances, Balanced

Pressure Percent (Maximum)	Average y Velocity (in/s)	Average z Velocity (in/s)	Pitch Rate (rad/s)	Yaw Rate (rad/s)
0.96	10.6	5.5	4.2	1.3
1.00	10.3	6.1	3.8	1.2
1.04	10.5	8.6	3.4	1.0

Another parameter that is believed to affect fall of shot is the initial orientation of the bullet as it sits inside the weapon chamber. Modern day KE rounds consist of a double ramped sabot with the rear ramp, or bulkhead, sealing off the propellant gas. The forward bell, or front ramp, typically has several thousands of an inch clearance between its outer diameter and the inner diameter of the gun tube. This clearance allows the bullet to cock slightly inside of the gun tube when it is loaded. Table 5 gives the results from a series of simulations that examine differences in bullet initial seating. For the DM13 bullet, this allowed the projectile to tilt up to 0.134°. Row 1 in Table 5 presents the exit state differences for a bullet tilted upward the maximum amount. Row 2 presents the results when the bullet is tilted only half that amount, and row 3 presents the norm when the bullet is not titled. Rows 4 and 5 tilt the bullet downward initially. In row 4, the tilt is one-half, and in row 5, the tilt is the maximum amount that would be possible. As can be seen in the table, the initial conditions of the bullet have a much larger effect on exit shot conditions than pressure variations.

Table 5. Projectile Initial Seating

Projectile Tilt (°)	Average y Velocity (in/s)	Average z Velocity (in/s)	Pitch Rate (rad/s)	Yaw Rate (rad/s)
0.134 ↑	35.2	20.6	7.2	4.7
0.067 ↑	42.9	14.0	10.9	3.2
0.0	40.7	11.3	−3.6	4.0
0.067 ↓	56.8	19.1	12.9	2.0
0.134 ↓	69.3	19.1	11.2	2.6

3. SUMMARY

The numerical model developed during this study allows the examination of subtle nuances of gun and bullet designs and their effects on projectile performance to be studied in detail. These techniques can also be coupled with experimentation to improve the numerical approximations and expand or otherwise help explain observed projectile gun tube interaction. Although the use of these elaborate

techniques to solve ballistic problems are in their infancy,* efforts are underway to utilize this technology to streamline the design and test procedures currently in practice for developing new tank munitions. One such step that is underway is to examine changes in KE projectile design and fabrication by evaluating their exit state conditions using techniques similar to the ones presented herein. Figure 6 shows a KE projectile that includes many of the bullet details which were overlooked in this preliminary study. Models such as the one shown in Figure 6 will allow the examination and analysis of future materials and new geometries to help optimize a bullet prior to testing. Hence, near future efforts will include an emphasis to improve and streamline the numerical methodologies presented here, allowing a more timely and accurate assessment of gun and projectile performance.

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* Far more needs to be done to quantify and correlate the numerical results from this type of analysis.

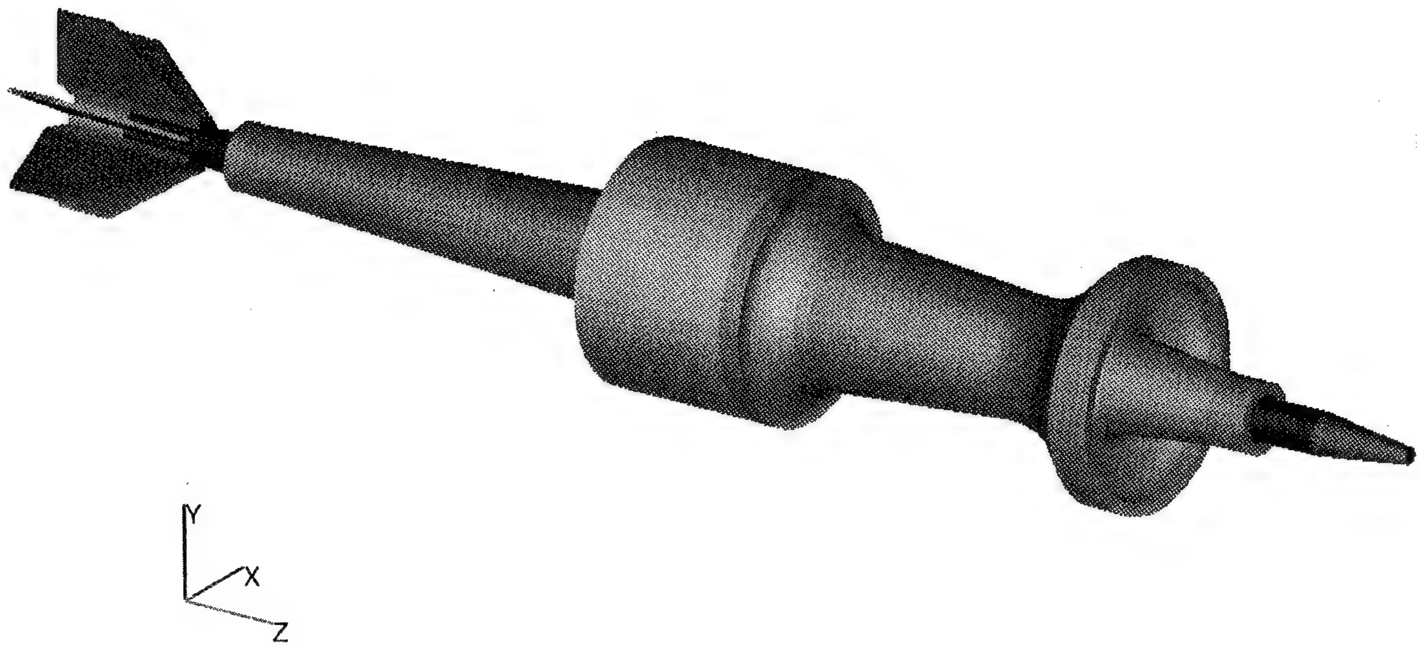

Figure 6. Detailed model of a modern KE projectile.

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